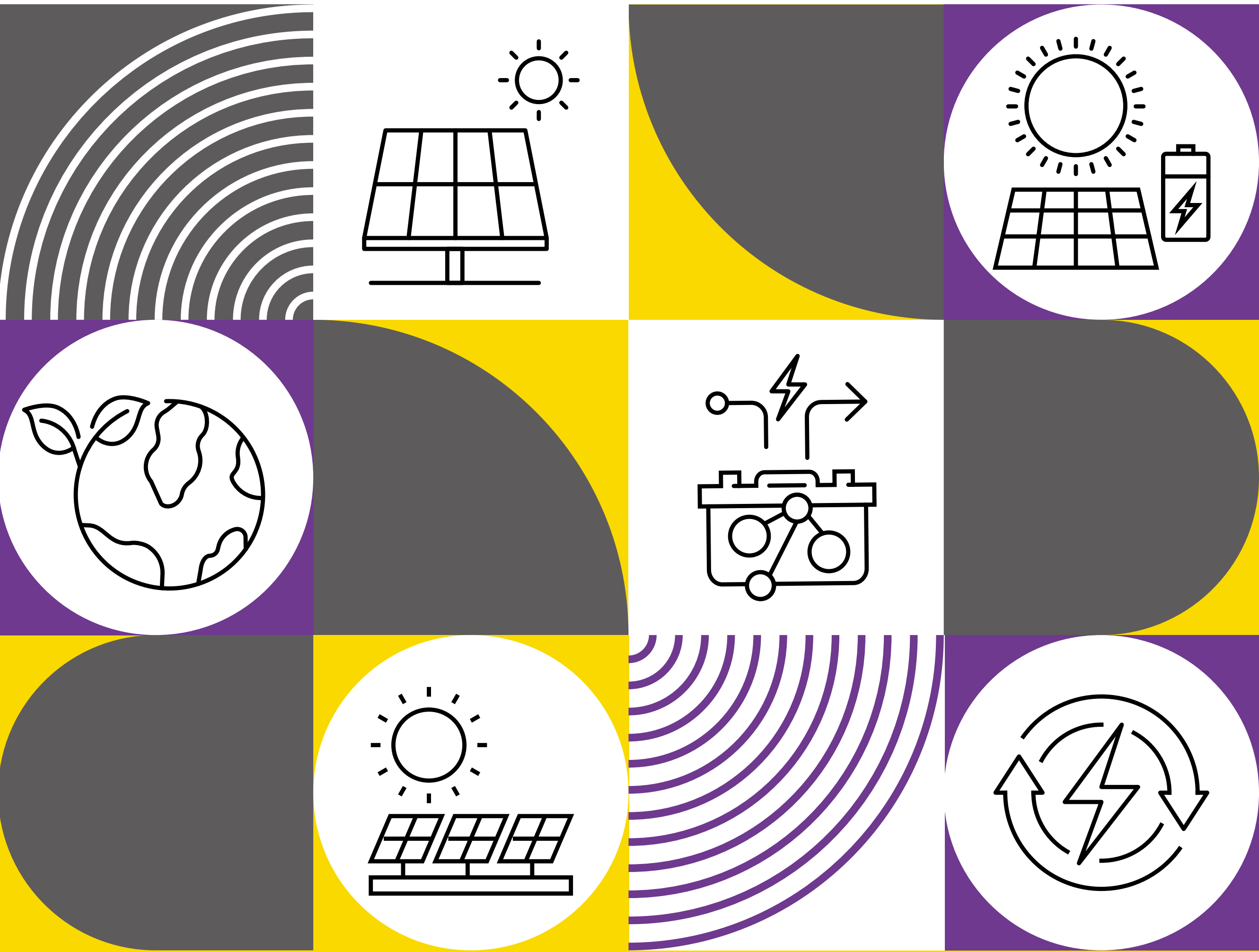
IRENA coalition FOR ACTION

KEY ENABLERS FOR THE ENERGY TRANSITION

SOLAR AND STORAGE



ISBN: 978-92-9260-682-4

Citation: IRENA Coalition for Action (2025), *Key enablers for the energy transition: Solar and storage*, International Renewable Energy Agency, Abu Dhabi.

About the Coalition

The IRENA Coalition for Action brings together leading renewable energy players from around the world with the common goal of advancing the uptake of renewable energy. The Coalition facilitates global dialogues between public and private sectors to develop actions to increase the share of renewables in the global energy mix and accelerate the energy transition.

About this publication

Produced by the Coalition's Towards 100% Renewable Energy Systems Working Group, this report presents case studies, best practices and policy recommendations for the transformation to 100% renewable energy systems enabled by electrification, efficiency and storage. The decarbonisation of the entire energy system is considered from the perspectives of energy suppliers and end users, with attention to innovation, technology, policy and socio-economic factors.

Acknowledgements

The Coalition's Towards 100% Renewable Energy Systems Working Group is led by Rainer Hinrichs-Rahlwes, vice-president of the European Renewable Energies Federation (EREF), and Dave Renné, former president of the International Solar Energy Society (ISES).

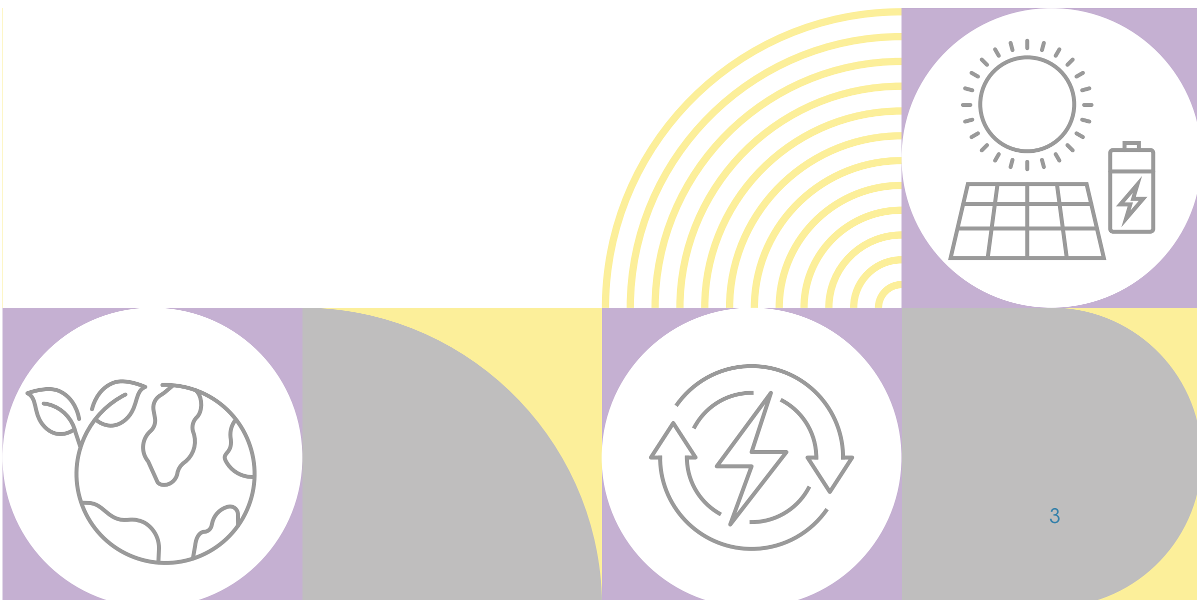
The report was co-authored by Xiangfeng Meng, Kangqiao Huang and Xiaobo Chen (Contemporary Amperex Technology Co., Limited, CATL), Rainer Hinrichs-Rahlwes (EREF), Dave Renné (ISES) and Jarred McCarthy (IRENA), and edited by Steven Kennedy.

Valuable contributions were provided by the following Coalition Members: Morjana Moreira dos Anjos, Andrzej Ceglarz and Alexandros Fakas Kakouris (Renewables Grid Initiative); Eric Quiring (SMA Solar Technology); Francesca Celletti, Yelizaveta Ramisheuskaya and Matteo Miccoli (Enel Green Power); Oghosa Erhahon and Gabriel Murtaugh (Long Duration Energy Storage Council); Alex Campbell (formerly of the Long Duration Storage Council); Kexin Mao and Raven Liu (Huawei); Giorgia Epicoco (formerly of Huawei); Itamar Orlandi and Jacob Roberts (Pexapark); Máté Heisz, Antonio Arruebo, Raffaele Rossi and Simon Dupond (SolarPower Europe); Subrahmanyam Pulipaka, Shubhang Parekh and Muskaan Sethi (National Solar Energy Federation of India); Melody Fu, Lin Sun and Quan Cheng (JinkoSolar); Merritt Zhang (China Photovoltaic Industry Association); Eddie Rich and Gordon Edge (International Hydropower Association); Mohammad Hassan Ghafouri, Sama Hamel, Fatemeh Hessami and Golshan Mir Moghtadaei (SATKA Association); Asma Al Bahjary (Women In Renewable Energy); Monica Oliphant (World Wind Energy Association); Roque Pedace (International Network for Sustainable Energy); Vivek Mittal (Africa Infrastructure Development Association); Léo Echard and Abdallah Alshamali (Global Solar Council); Steven Vanholme (EKOenergy ecolabel); Stephan Singer (Climate Action Network International); and Andrea Wainer (REN21); IRENA colleagues Ilina Radoslavova Stefanova, Giedre Viskantaite, Jan Mola, Julian Prime, Jinlei Feng, Abdullah Fahad, Hannah Guinto, Larissa Pinheiro Pupo Nogueira, Jaidev Dhavle, Francisco Gafaro, Adrian Gonzalez and Deborah Machado Ayres, all under the guidance of Ute Collier (Acting Director, IRENA Knowledge, Policy and Finance Centre); and former IRENA colleagues Bohan Liu, Carlos Ruiz and Raúl Alfaro Pelico. Technical review was provided by Paul Komor (IRENA).

The IRENA Coalition for Action would also like to express its gratitude to all of the members of the Towards 100% Renewable Energy Working Group who participated in the events and discussions that informed these findings.

Editorial and publishing support was provided by Francis Field and Stephanie Clarke, with design provided by Myrto Petrou.

CONTENTS



ABBREVIATIONS

CAISO	California Independent System Operator
COP	Conference of the Parties
EES	electrical energy storage
GW	gigawatt
IEC	International Electrotechnical Commission
IRENA	International Renewable Energy Agency
kWh	kilowatt hour
LCOE	levelised cost of electricity
LDES	long-duration energy storage
MACSE	Meccanismo di Approvvigionamento di Capacita di Stoccaggio Elettrico (Italy) (electric storage capacity procurement mechanism)
PV	photovoltaic
R&D	research and development
SDG	Sustainable Development Goals
TW	terawatt
UAE	United Arab Emirates
USD	U.S. dollar
VRE	variable renewable energy

EXECUTIVE SUMMARY

Against the backdrop of the First Global Stocktake and the United Arab Emirates (UAE) Consensus, which set targets to triple renewable power capacity and double energy-efficiency improvements by 2030, with a base year of 2022. The 29th United Nations Conference on Climate Change, Conference of the Parties (COP29) Presidency further called for a sixfold increase in global storage capacity to 1500 gigawatt (GW), a doubling of grid investment, and 25 million kilometres (km) of new transmission and distribution lines by 2030. A total of 65 countries, alongside major industry players, committed over USD 117 billion annually to grids and renewables during COP29, with nearly half earmarked for grid infrastructure.

Global electricity demand grew 4.3% in 2024, and demand is expected to accelerate further with the proliferation of large data centres and expanding electrification of transport, industry and other sectors (IEA, 2025). In 2024, 582 GW of new renewable capacity came online, with solar photovoltaic (PV) accounting for 452.1 GW. Overall, 91% of all additions were renewable (IRENA, 2025a). Solar PV emerges as one of the most cost effective solutions to meet surging demand. A solar PV plant's capacity can be further increased by 2-3 times with storage.

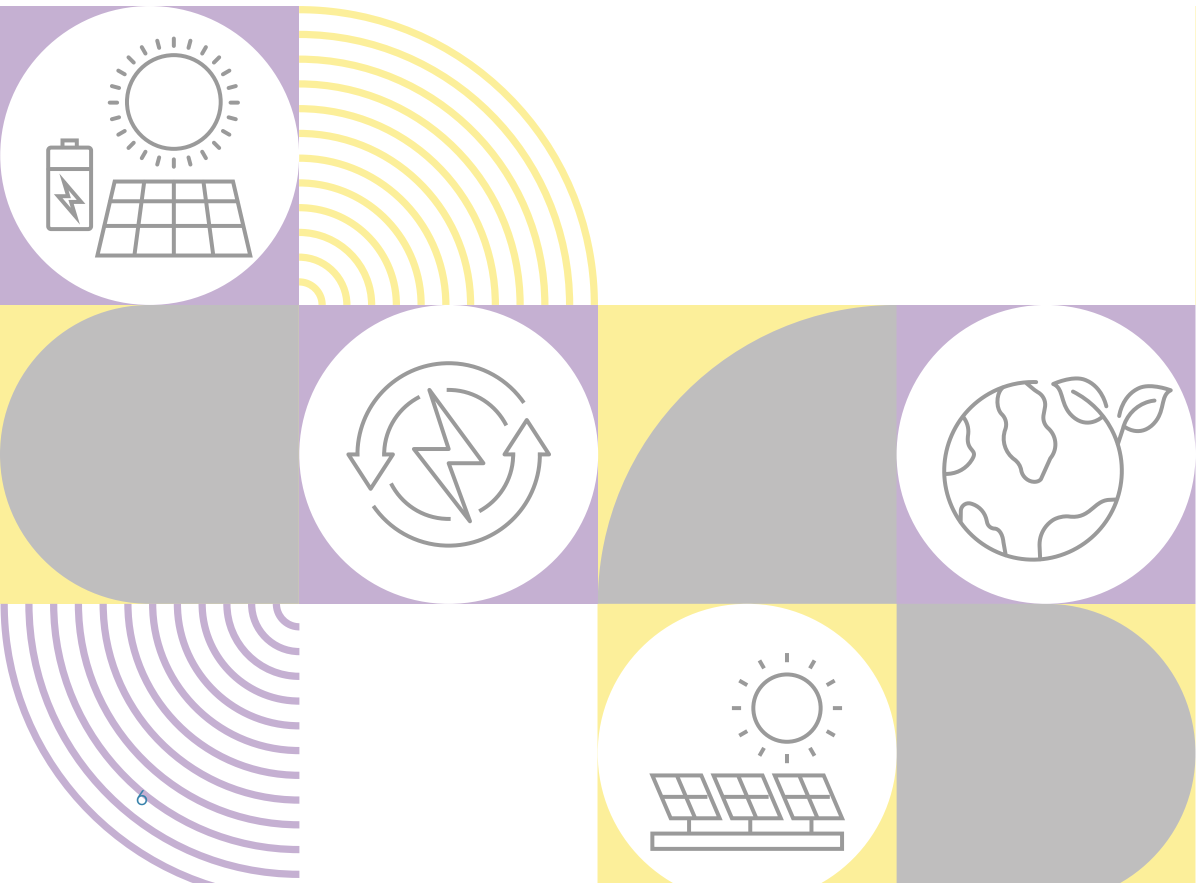
Storage systems are essential for grid flexibility, reliability and affordability as variable renewable energy (VRE) replaces conventional plants. This is because storage systems make it possible to mitigate curtailment (periods when generation exceeds demand) by storing excess energy and discharging it when needed. Given their different response characteristics and round-trip cycle efficiencies, storage technologies can complement each other in a cost-effective and reliable power system. Additionally, batteries equipped with grid-forming inverters can provide voltage and frequency services that contribute to grid stability and enable higher penetration of solar energy. Beyond batteries (which cover response times from microseconds to around eight hours), long duration storage (>8 hours) and pumped hydro (daily to seasonal shifts) are critical for matching supply with load variations and maintaining firm dispatchable power.

Developed by IRENA's Coalition for Action Working Group Towards 100% Renewable Energy Systems, this publication identifies policy recommendations and best practices to guide the energy transition. Key recommendations include:

- **Promote storage as a key enabler for the global tripling target.** Storage capacity targets must be adopted to drive investment and ensure long term commercial viability of storage industries. Skill gaps in the workforce should be addressed through targeted action plans.

- **Enhance grid flexibility and stability via energy storage.** Governments should develop regulatory frameworks, market-based solutions, and investment mechanisms that facilitate grid forming solutions, align storage deployment with local flexibility needs, and secure financing for integrated grid-storage assets.
- **Develop solar PV and storage through favourable financing and insurance policies.** Fiscal incentives, from capital subsidies to performance based rewards, coupled with innovative insurance products, are needed to lower the barriers posed by high upfront costs and policy uncertainty, thereby bolstering investors' confidence in solar PV and storage projects.
- **Support the development of standards and certifications.** International co-operation via technical committees must advance global safety, performance and life-cycle standards for storage technologies, while also supporting supply chain diversification and innovation in life-cycle assessment and recycling.

By implementing these measures, policy makers and industry stakeholders can significantly advance the decarbonisation of power systems, meet the 2030 renewable capacity and storage targets, and lay the foundation for a resilient, fully renewable global energy system.



1. INTRODUCTION

This report focuses on the role of storage technologies as key enablers of a significant expansion of renewable energy technologies, especially variable renewable energies (VRE) such as solar photovoltaics (PV) and wind in electricity grids around the world. In 2023, targets for tripling renewable energy power capacity to 11.2 terawatts (TW) and doubling the rate of energy efficiency improvements by 2030 were a key outcome of the First Global Stocktake at the 28th Conference of the Parties (COP28) in the United Arab Emirates, known as the UAE Consensus (IRENA *et al*., 2024). Complementing this call for action, the COP29 Presidency of Azerbaijan sought to secure a global pledge to increase energy storage capacity sixfold to 1500 gigawatts (GW), double global grid investments and develop 25 million kilometres (km) of transmission and distribution lines by 2030. This pledge is supported by 65 countries (as of July 2025), and over 100 non-state actors (COP29 Presidency, 2024). In addition, several industry leaders reinforced their commitment of more than USD 117 billion annually to investments in grids and renewables, with around 48% of the committed investment earmarked for grid infrastructure (IRENA and UNEZA, 2024). Achieving these ambitious targets and goals will require innovative approaches to technology and policy that will have to continue beyond 2030.

In 2024, global electricity demand rose by 4.3%; further growth is expected in the coming years, driven by record temperatures, electrification and digitalisation. A substantial share of this growth is being met by renewable electricity as new global renewable capacity additions reached an unprecedented 582 GW in 2024, a 19.8% increase from 2023, and accounting for 91% of all new power generation capacity (IRENA, 2025a). Of the 582 GW, 452.1 GW, or 77%, was attributed to solar PV, with China alone adding 276.8 GW followed by the United States (37.7 GW) and India (24.5 GW) (IRENA, 2025a). Notably, 91% of new renewable power projects commissioned in 2024 were also more cost-effective than any fossil fuel-fired alternative (IRENA, 2025b). Solar PV combined with energy storage has become one of the most cost-effective ways of meeting growing electricity demand and will be key to achieving the COP28 goal of tripling capacity – with 587 GW of the 1044 GW of annual additions through 2030 coming in the form of solar PV – and the storage goal of 1500 GW promoted by the COP29 Presidency (IRENA *et al*., 2024).

Storage solutions enhance grid flexibility and reliability under increasing penetrations of VRE. Since renewable energy will be replacing traditional centralised generating stations such as coal and nuclear plants, as well as many fossil-powered peaking plants, in the next few years, grid, storage solutions will be needed to maintain firm dispatchable power and grid reliability.

Energy storage can also minimise the risks of curtailment arising when more solar energy comes into the grid than is needed to meet demand, complementing enhanced grid infrastructure, market reforms, and advanced forecasting and other flexibility options (IRENA, 2024a, 2024b).

Solar PV and storage can allow for a power system that is more distributed than what currently exists and can also be the basis for community and micro grid systems, thereby lessening the need for major new grid infrastructure and supporting universal energy access, affordability and climate adaptation and mitigation efforts. The transformation to a more distributed power system will reshape market forces and necessitate changes in the regulatory environment to enable more distributed and flexible grid systems. In addition, a more distributed renewable electricity supply combined with storage technologies is key to a resilient grid that presently is being seriously affected in many regions by weather phenomena associated with climate change, such as more intense storms and greater risk of forest and rangeland fires (IRENA and WMO, 2023).

The storage technologies detailed in this paper address a range of time frames: battery storage for maintaining grid reliability and quality in time frames typically from micro-seconds to ~8 hours; long duration energy storage for shifting electricity supply to meet load variations >8 hours, including pumped hydro, which in and of itself can also maintain for an even longer term (daily, weekly, even seasonal shifting of supply). This report is part of the International Renewable Energy Agency's (IRENA) partnership initiative: The Coalition for Action and was developed through the Coalition's Towards 100% Renewable Energy Systems Working Group. This working group highlights best practices and policy recommendations for the transformation to 100% renewable energy systems to meet the energy demands of all end-use sectors. The range of issues presented by storage is varied and wide; it includes cost savings from avoided grid expansions, reduced curtailment, improved system efficiency, and deferred new capacity investments, as well as the contribution of all of these to climate resilience and energy access. It would not be possible to cover the full range of topics in a single report. The Working Group therefore anticipates the development of future reports addressing other issues related to the transformation of power systems.

This report highlights the role of storage in meeting global renewable power capacity targets and system requirements. It further underscores the need for new national and regional policies, as well as an enabling regulatory environment to ensure that future electricity systems can function flexibly and reliably as VRE penetration grows.

The report is organised as follows. Chapter 2 examines the current state of solar PV and key supporting storage technologies, while laying out the rationale for enhancing grid flexibility to allow for greater inclusion of solar PV. Chapter 3 discusses how storage technologies are being factored into grid expansion and modernisation plans; it also offers an overview of how effective policies and financing mechanisms will facilitate the deployment of integrated solar storage solutions. It argues that battery storage technologies operating in grid systems must follow rigorous codes and standards. Chapter 4 presents a series of recommendations that support the international target of tripling renewable energy by 2030 and ultimately achieving 100% renewable energy systems. The Annex provides applied best-practice case studies of systems using solar PV and storage.

2. SOLAR PV AND STORAGE STATUS AND TRENDS

Solar PV and storage solutions can be highly effective in supporting renewable energy integration and end-use electrification. Solar PV is growing fast because of its declining costs and growing role in reducing emissions. The global weighted average levelised cost of electricity (LCOE) for solar PV increased marginally by 0.6% from 2023 to 2024, reflecting changing trade and financial conditions (IRENA, 2025b). Nevertheless, between 2010 and 2024, solar PV's LCOE decreased 90%. The global weighted average LCOE for utility-scale solar PV in 2024 reached USD 0.043/kilowatt hour (kWh), making it 41% cheaper than the least-expensive fossil fuel alternative (IRENA, 2025b). A few key storage statistics appear in Box 1.

Box 1 Key statistics on storage

- The globe's cumulative installed electrochemical battery storage capacity was 158 GW as of 2024 (BNEF, 2024, 2025).
- The cumulative power capacity of pumped hydropower was 150 GW as of 2024 (IRENA, 2025a).
- Long-duration energy storage (LDES) amounted to 12 GW in 2023. LDES offers the ability to discharge continuously for eight hours or more, with the energy stored over periods across days, weeks and even seasonally. LDES includes mechanical storage such as flywheels, gravity-based and compressed air energy storage (LDES Council, 2024).[a]

Source: (BNEF, 2024, 2025; IRENA, 2025a, 2025b).

[a] Pumped hydropower is considered an LDES technology. But owing to the shear capacity of pumped hydropower compared with other LDES technologies, it will be analysed separately in this report.

Furthermore, utility-scale energy storage costs declined 93% between 2010 and 2024, from USD 2 571/kWh to USD 192/kWh, driven by technological advancements in battery chemistry, manufacturing improvements and optimisations, among other factors (IRENA, 2025b).

Storage solutions are diverse and include a variety of short- and long-duration technologies. These technologies have respective advantages in terms of costs, energy efficiency, safety, and maturity; they vary in their uses and their development potential. Innovative solar PV and storage solutions as well as policy and financial mechanisms that enable the sustainable development of the renewable energy industry are needed to ensure that energy storage and grid development keep pace with the growing deployment of renewable energy sources.

2.1 Global trends in the solar PV industry

Technological advancements, falling costs and increased awareness of climate change are driving the global expansion of solar PV markets. This trend is enabling more countries worldwide to capitalise on their solar potential and pursue sustainable energy goals.

A total of 1858.7 GW of solar PV systems have been installed globally to date, with 452.1 GW commissioned during 2024 alone, representing a 32.1% increase over 2023 (IRENA, 2025a).

Regionally, Asia continued to dominate solar PV installations in 2024, driven mainly by China, which installed 276 GW (61%) of the 452.1 GW installed globally (IRENA, 2025a). China has pledged to peak its carbon dioxide emissions before 2030 and to achieve carbon neutrality before 2060, which is fuelling the rapid growth of local solar PV and other renewable energies. By the end of 2024, China's cumulative installed capacity of solar PV surpassed 886 GW (IRENA, 2025a). However the rapid expansion of VRE installations and power generation in China, including solar PV, has posed serious challenges as the swift growth outpaces the rate of grid upgrades, leading to increased demand for higher voltage transmission and more grid-compatible energy storage solutions (CPIA, 2024). China has put policies in place to address these challenges. Among those policies is the Action Plan for Accelerating the Construction of a New Power System (2024-2027), which outlines nine specific actions to enhance the grid's integration, allocation and regulation of renewable energy. The Action Plan includes provisions for constructing shared energy storage stations, exploring new energy storage technologies, and revising grid-connection technical standards and management requirements to improve the power system's stability through better co-ordination among generation, grid, load and storage (NDRC, 2024).

India added 24.5 GW of solar PV in 2023, reaching 97 GW of cumulative capacity (IRENA, 2025a). Several factors contributed to the high growth. One was a government flagship scheme launched by Prime Minister Shri Narendra Modi in February 2024. The scheme – PM–Surya Ghar: Muft Bijli Yojana – aims to provide free electricity to households (Government of India, 2025). Households will be provided with a subsidy to install solar panels on their roofs, covering up to 60% for the first 2 kW and 40% of the additional cost up to 3 kW. Another key step has been the Renewable Purchase Obligation targets, launched by the government in 2023 to mandate an increasing share of renewable energy in the total energy mix through 2030 (BEE, 2025).

While India is looking to accelerate its installations through timely policy interventions and incentives, Indian solar manufacturing capacity is also set to take off. The National Solar Energy Federation of India projects that India will become the world's second-largest manufacturer of solar modules, with a total capacity of 78 GW by 2025 and 100 GW by early 2027 (NSEFI, 2025). Despite the growing capacity, timely availability of additional grid capacity stands out as a key bottleneck to achievement of India's ambitious targets in the coming years. The need to establish transmission systems in states with lower solar resources is yet another impediment, as is the availability of land.

To address these issues, local governments must identify potential hubs where solar PV and storage can be stationed. A promising example is the Green Energy Corridors Initiative, whereby dedicated transmission networks can enhance renewable integration into the national grid. Another possible solution is to combine solar generation with agriculture activities (agrivoltaics) for low-risk crops including horticulture (SolarPower Europe, 2024a).

Outside of Asia, renewables markets continued to gain momentum in 2024. These markets included additional capacities from the United States (37.6 GW), Brazil (15.1 GW), and Germany (15 GW) (IRENA, 2025a). In the European Union (EU), solar PV supplied nearly 10% of the total electricity consumption in 2023; installed capacity is projected to reach 816 GW by 2030 (SolarPower Europe, 2024b). Between 2021 and 2023, the EU market maintained a steady annual growth rate of 40%-50%, driven by technology cost decreases, climate and energy targets and, most importantly, reduced energy import dependencies (to increase energy security). Difficulties remain, however, for the EU's solar PV deployment. Countries with high shares of VRE, and in particular solar PV, are struggling with how to integrate VRE smoothly into their power mixes.

These challenges are both technical and financial.

From a technical perspective, solar energy is wasted through curtailment in times of low demand and high electricity generation. The challenge of curtailment needs to be addressed and mitigated by unlocking investments in storage and other flexibility options across the energy system and at all levels: distributed, large-scale and seasonal (SolarPower Europe, 2024a).[1]

From the financial point of view, abundant production of solar electricity in unflexible systems and markets brings down the electricity price, often below zero. The lack of electricity demand, storage capacities or demand-side flexibility are threats to the viability of solar projects (SolarPower Europe, 2024a). Outdated inflexible markets and systems prevent consumers from benefiting from the low costs of renewable energy.

[1] *There is no aim for zero curtailment, as this is neither economically viable nor, in many cases, operationally optimal (O'Shaughnessy, Cruce and Xu, 2021). Efficient levels of curtailment in a flexible grid is what is required.*

In Sub-Saharan Africa, nations like South Africa are investing heavily in solar projects and seeing high-capacity growth. In the Americas, Brazil is leading Latin America in solar installations, with supportive regulations and substantial solar resources. Other countries in the region, including Mexico, Chile and Argentina, are also experiencing steady growth in PV deployment. In the Middle East and North Africa, Egypt, Morocco, the United Arab Emirates and Saudi Arabia are emerging as significant players, with ambitious renewable energy targets and large-scale solar farms to diversify their energy portfolios away from fossil fuels (IRENA, 2024c).

Solar supply chains and job creation represent a critical aspect of global growth trends. The volume and extent of the solar PV value chain is currently driving the development of local employment and skills all over the globe, making the energy transition not only economically viable but also socially sustainable and desirable. Countries can enhance the resilience of their solar PV supply chain and facilitate greater market access through diversification, localisation and participation, and conformity with international quality standards. Environmental, social and governance (ESG) aspects for solar PV provide further confirmation on the sustainability of the technology itself (IRENA, 2024d).

Global solar PV employment grew sharply from 4.9 million in 2022 to 7.1 million in 2023 (IRENA and ILO, 2024). The five countries with the highest solar PV employment are: China, with 4.6 million jobs (or 65% of global PV jobs), India (318 600); the United States (279 000); Brazil (264 000); and Germany (154 700) (IRENA and ILO, 2024). That said, the sector still faces a shortage of skilled labour. Based on the capacity trends, a larger and more skilled local solar workforce is needed. This need will require the attention of policy makers globally.

2.2 Global landscape of storage technologies

Energy storage has long been a key component of efforts to minimise electricity system costs. At the most basic level, storage works by providing energy shifting (*e.g.* storing electricity at times of relative surplus to be released when wholesale prices or generating costs are higher) and ancillary services to the grid. As the electricity system transitions from large thermal power plants to one dominated by variable solar and wind energy, storage will become increasingly important (IRENA, 2024c). All forms of energy storage technologies are essential for the energy transition to meet specific use-case needs.

2.2.1 Classification of energy storage technologies

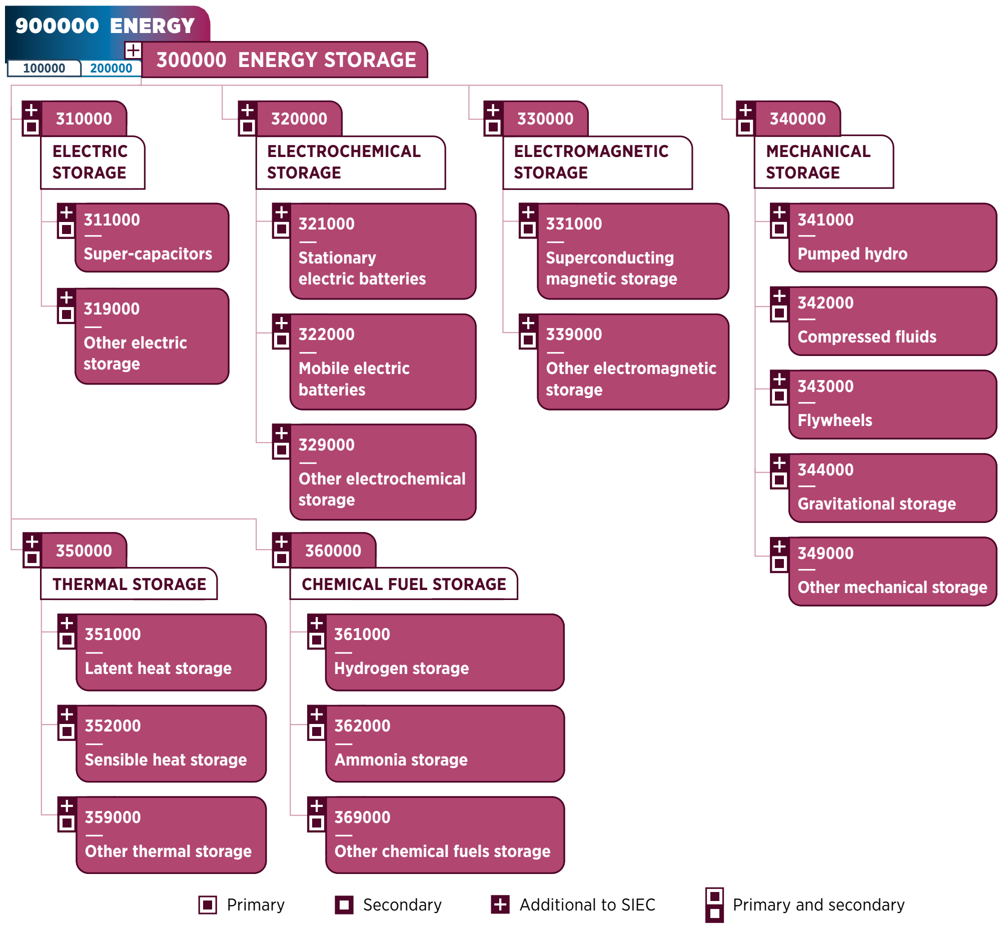
As with other segments of the energy system, storage is undergoing rapid technological innovation, industrialisation of new technologies, and cost reductions.

Today, a variety of energy storage technologies are available, including electrochemical storage, mechanical storage, thermal storage and chemical storage, among others. Figure 1 shows the IRENA classification of energy storage by technology, corresponding to the Standard International Energy Product Classification (SIEC), as well as (IRENA, 2024e).

IRENA further elaborates on the categories of energy products:

- Primary: energy products from natural energy flows, entering the energy system for the first time
- Secondary: energy products from primary, or other secondary fuels or energy sources
- Primary and secondary: Occurring either as primary energy, or as products of primary or secondary energy sources (IRENA, 2024e).

Figure 1 **Classification of energy storage**



Source: IRENA, 2024e.

The subsections that follow will focus on the three most widely deployed types of storage technology used on electricity grids today. These are:

- electrochemical storage (electrochemical storage, primarily lithium-ion);
- pumped hydropower (mechanical storage); and
- long duration energy storage with the ability to discharge continuously for eight hours or more, with the energy stored over periods across days, weeks and even seasonally. This includes all other forms of storage with the exception of chemical fuels storage (and as noted prior pumped hydropower).

2.2.2 Electrochemical storage

Electrochemical storage (*i.e*. batteries), is the most widely used storage technology in the power sector based on installed capacity, totalling 158 GW as of 2024 (BNEF, 2024, 2025). Over 69 GW of stationary battery storage capacity was added in 2024 globally - almost double the total capacity of 89 GW in 2023 (BNEF, 2024, 2025). Installed stationary battery storage capacity is predicted to grow to an estimated 782 GW (2013 GWh) by 2030, however, IRENA's 1.5C Scenario (IRENA, 2024f) indicates that for long-term decarbonisation, grid-scale storage, including both utility-scale and behind-the-meter battery storage, is needed and would have to reach up to 900 GW by 2030.

Between 2010 and 2024, battery storage project costs declined 93%, from USD 2 571/kWh to USD 192/kWh, achieved through scaled-up manufacturing, improved materials efficiency and improved manufacturing processes (IRENA, 2025b).

Lithium-ion battery storage continues to account for most of the electro-chemical storage technologies being installed. Lithium-ion battery storage is well-suited to provide short-term flexibility as well as a broader range of ancillary and reserve services, such as assuring system adequacy and managing congestion in transmission and distribution systems (IEA, 2024b). It is especially good at providing frequency regulation and voltage support in power grids owing to its millisecond-level rapid response capabilities. Due to its advantages in construction time, flexible siting, and capacity configuration, it can be deployed for grid flexibility by being paired with VRE, stand-alone ancillary storage services, and demand response.

Depending on demand, lithium-ion batteries currently provide roughly 2-4 hours of power. As the need for longer-duration storage grows, the industry is adapting to provide sufficient capacity of at least 4-8 hours. For example, new commercial projects in Italy are tendering lithium-ion batteries for 8-hour storage (Reuters, 2025).

China is the leading market for battery storage, adding 23 GW of capacity in 2023. This amounts to 55% of global capacity additions in 2023. The United States is the second-largest battery storage market, doubling its capacity to 8 GW in 2023. Installed battery storage capacity in the European Union increased by 70% in 2023, adding 6 GW (IEA, 2024b). Within Europe, Germany added 3.79 GW, followed by Italy (1.96 GW), and the United Kingdom (1.37 GW). In Australia, the annual deployed capacity was 0.94 GW; in South America, it amounted to 0.33 GW (Bloomberg, 2025).

2.2.3 Pumped hydro

Pumped hydro has historically dominated the global energy storage landscape owing to its large capacity, long-duration capabilities and ability to provide services such as load shifting and peak shaving (IHA, 2025; IRENA, 2023). Globally, the total installed capacity of pumped hydro grew from 88.8 GW in 2000 to 150 GW in 2024, with 8.6 GW added in 2024 (IRENA, 2025a). China is the main driver of that growth. Over 90% of the capacity installed in 2024 (7.7 GW) is attributed to China (IRENA, 2025a).

Pumped hydro can be subdivided into two categories: 1) open-loop systems, which utilise a natural water source; and 2) closed-loop systems, which do not utilise a natural water source and generally have a lower environmental impact on their surroundings.

Pumped hydro can provide longer-term storage and be combined with other technologies to balance peak demand on the grid. Its overall benefit is that it can play a crucial role as a source of flexible power storage, enabling a much higher share of VRE generation and integration into the grid (IHA, 2025; IRENA, 2023). Pumped hydro storage also provides a range of grid services. Prominent examples are rotating inertia to maintain frequency regulation and voltage control, operating reserves and black start, all of which will be increasingly important in ensuring grid reliability (IHA, 2021).

After China, the largest pumped hydro market, comes Japan (21.8 GW), followed by the United States (18.9 GW), Germany (5.2 GW) and India (4.7 GW) (IRENA, 2025a). The global capacity of pumped hydro is expected to increase to 280 GW by 2030, short of the 320 GW that would be needed to remain on a Paris Agreement pathway according to IRENA's 1.5C Scenario (IHA, 2025; IRENA, 2024e). The dual need for system flexibility and decreasing dependence on fossil fuels is driving pumped hydro deployment, which is also being supported by incumbent schemes for demand response and storage (IHA, 2025). For example, China is poised to continue to cement its lead by targeting 120 GW of pumped hydro storage by 2030, with India also aiming high, with a target of 26 GW by 2032 (IHA, 2025).

In North and Central America, Africa, and South America, pumped hydro remains largely untapped, even though hydropower already meets the needs of over 40% of the power sector in Africa and South America. The first region is dominated by the United States (18.9 GW), with only one other country, Canada (174 MW), having installed pumped storage (IRENA, 2025a, IHA, 2025). In the Africa region, South Africa and Morocco are the only two countries with pumped hydro, at 2.7 GW and 814 MW, respectively. In South America, only Argentina (974 MW) and Honduras (6 MW) have installed capacity (IRENA, 2025a). Overall, outside of China, more international effort is needed to fully tap into pumped hydro resources globally.

2.2.4 Long-duration energy storage

Increasingly, regulatory authorities are introducing support mechanisms to incentivise the deployment of long-duration storage capable of discharging continuously for eight hours or more, with the energy stored over periods across days, weeks and even seasonally.

An estimated 12 GW of long-duration energy storage projects were deployed by the end of 2024, with around 23 GW expected by 2030 (LDES Council, 2024). This operational capacity is split between over 7 GW of thermal storage, just under 2 GW of mechanical storage (such as compressed air) and over 2 GW of non-lithium-ion battery storage. By 2030 the proportion of new types of mechanical storage is expected to exceed 13 GW deployed, while thermal storage is expected to reach nearly 8 GW and non-lithium-ion battery storage to approach 3 GW. Three-quarters of the 12 GW of deployed capacity is found in North America, where another 9 GW is under development (LDES Council, 2024). The viability and performance of long-duration energy storage technologies for extended storage needs are expected to improve as technology advances and practical experience grows. Early adoption and faster commercialisation are heavily dependent on favourable regulatory and policy frameworks (IRENA, 2025b; LDES Council, 2024).

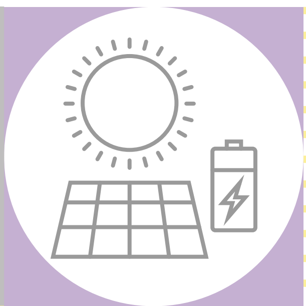
2.3. Cost trends in energy storage technology

The most economically viable storage technologies are pumped hydro and lithium-ion batteries. These are widely used compared with other storage technologies. As noted, between 2010 and 2024, battery storage project costs dropped by 93%, from USD 2 571/kWh to USD 192/kWh (IRENA, 2025b). Conventional pumped storage is still the most competitive technology, with a global average installed cost of USD 156/kWh for 6 hours of storage. Lithium-ion battery costs averaged USD 235/kWh for 6+ hours storage in 2023. Thermal storage, such as molten salt and solid state, has a global average installed cost of USD 238/kWh (IRENA, 2025b, 2024a). Pumped hydro costs are expected to remain stable through 2030 (NREL, 2024).

Since 2021, lithium iron phosphate (LFP, a type of stationary battery in the lithium-ion battery category) has been the dominant battery chemistry in the stationary energy storage market and is expected to remain on top through 2030 (IRENA, 2024a). Lithium-ion battery costs fell over the last few years for several reasons, including cheaper components, improvements in system integration, and advancements in deployment (IEA, 2023).

Costs for these other long-duration technologies range from USD 300/kWh for compressed air energy storage (CAES) to USD 658/kWh for gravity energy storage (BNEF, 2024; IRENA, 2025b). According to the LDES Council, the cost of novel electrochemical batteries were expected to range between USD 153 and USD 229 per kWh for an archetypal 8 hour/100 MW system, between USD 122 and USD 828 per kWh for mechanical storage, and between USD 110 and USD 232 per kWh for thermal forms of storage (LDES Council, 2024).

In summary, all storage technologies, given their different response characteristics and round-trip cycle efficiencies, can complement each other in a cost-effective, reliable and flexible power system (IHA, 2021).



3. STORAGE TECHNOLOGIES TO ACCELERATE RENEWABLE ENERGY DEPLOYMENT

This chapter discusses the roles storage technologies can play in making the grid more reliable and resilient and improving its ability to accommodate high amounts of VRE.

The successful deployment and commercial success of any renewable technology has three main components: 1) technological innovation; 2) access to finance, whether public or private; and 3) enabling policies at all levels of governance. The interaction among these three pillars is strong: Successful technologies attract financing and successful enterprises, and successful enterprises stimulate policy decisions to further their growth and attract additional financing, while at the same time contributing to economic growth and job creation.

Section 3.1 highlights the role of storage in grid expansion and modernisation plans, expanding on the technical aspects of storage technologies. Section 3.2 deals with the financing aspects and types of policies needed to incentivise storage technologies. Section 3.3 addresses standards and certifications as parts of any successful commercial storage enterprise. Standards and certifications ensure that storage technologies operate safely and as expected.

3.1 Storage in grid expansion and modernisation plans

Balancing supply and demand at all times is crucial for a power system's reliable operation. Even a small mismatch can disturb the system's frequency and affect the reliability of system operations. Power system flexibility here is defined as "the ability of a power system to reliably and cost-effectively manage the variability and uncertainty of demand and supply across all relevant timescales" (IEA, 2018).

Around the world, power networks are struggling to keep pace with the surging deployment of renewables and with increasing requests for grid connection. In 2023, an estimated 1 500 GW of renewable energy projects in the late stages of development or under review were awaiting grid connection, and this figure doubles to an estimated 3 000 GW when projects in the earlier stages of development are also considered (REN21, 2024). The lack of balancing power, reactive loads, inertia and proper short-circuit levels (SCL) in almost all grids can compromise grid stability. This is where storage systems become critical. When high penetrations of VRE are in place, storage technologies can provide grid services at many time scales, ranging from short-term frequency modulation to mid-term balancing power and longer-term dispatch for maintaining baseload supply. For example, battery storage is increasingly being adopted for purposes of frequency regulation, replacing traditional methods, whereas pumped storage power plants offer large-scale energy storage and can compensate for temporary loss of generation facilities (IEA, 2023).

VREs are becoming the system-defining technologies globally, and wind and solar power will continue to be the dominant energy sources in many electricity systems. This being so, the rapid growth in renewable capacity must be accompanied by the deployment of crucial enabling infrastructure. By enabling electricity grids to integrate renewables at all voltage levels, regions can stay on track towards a timely and cost-efficient energy transition, boosting energy security and competitiveness, and allowing societies and industries to leverage the multiple benefits of infrastructure improvements.

In 2023, investments in electricity grids and flexibility sources to integrate higher shares of solar and wind power were USD 368 billion – around half of the USD 720 billion on average that is required each year between 2024 and 2030 to meet the international goal of tripling renewables-based power by 2030 (IRENA, 2024a).

Moreover, existing grids are ageing. In 2021, only around 23% of the grid infrastructure in advanced economies was less than 10 years old, and more than half was more than 20 years old (IEA, 2023). Power transformers, which play a critical role in electricity grids, typically have a design lifetime of 30 to 40 years (IEA, 2023). These figures translate into a need to add or refurbish a total of over 80 million kilometres of grids by 2040, the equivalent of the entire existing global grid, complemented by flexibility solutions.

The integration of a high proportion of grid-connected VRE poses challenges to grid stability. Implemented alongside solar PV, energy storage has the potential to mitigate some of the investment required to stabilise grid infrastructure. Energy storage can be used to increase the capacity factor of existing transmission lines, thus reducing the need for investment in new transmission lines. Some estimates foresee that new renewable capacity, particularly decentralised solar PV, is increasingly connecting at the distribution level, especially in residential, small commercial, and community segments (O'Shaughnessy and Shah, 2021). In this context, targeted grid upgrades combined with storage and demand-side flexibility could defer or reduce the need for costly investments in traditional grid reinforcement and large-scale transmission infrastructure (IRENA, 2019).

Storage technologies applied to the electricity grid will require appropriate technical characteristics, such as response time, to provide the needed flexibility and services (Denholm *et al*., 2010). In the short- to medium-term, batteries can offer a wide range of services in addition to those offered by pumped hydro (IEA, 2023). Over longer time periods, as previously noted, long-duration technologies such as pumped hydro, compressed air energy storage (CAES), long-duration batteries and thermal storage will contribute to grid flexibility. Grid digitalisation will also play a key role in these infrastructure improvements.

3.2 Solar PV and storage in energy markets

Siloed policy making continues to hinder the systemic shifts required in energy policy and planning for solar PV and storage systems. This section addresses three topics: 1) energy market operations; 2) policies and financial incentives needed to provide investment signals, sustainable business models and market mechanisms; and 3) insurance mechanisms.

3.2.1. Operation within the energy market

A common hurdle faced by storage operators in many jurisdictions is double taxation and double wheeling charges. Because of its dual role as both a generator and a load, storage may be taxed both when charging and discharging, resulting in a systemic disadvantage compared to other technologies (IEA, 2024b). In such cases, establishing suitable market mechanisms where storage facilities can participate directly in the market is crucial. In China, some provinces have waived grid tariffs and taxes during charging to grant storage facilities direct access to the market. China is promoting the reform of market mechanisms to explore joint operations between renewable energy and storage and to explore new business models such as capacity leasing. Besides China, the European Union and its Member States such as Ireland, Italy, Portugal and Spain are in the process of reforming energy market mechanisms so that energy storage will become a stronger player in the electricity market.

To promote more investment in storage projects, market mechanisms must allow the stacking of revenue streams from a variety of storage services in different power markets. To permit this, revenue streams associated with energy (arbitrage), capacity (markets or mechanisms that reward dispatchability) and ancillary services (frequency response, voltage control, black start) must be discrete and visible. In markets where this is the case, such as the United Kingdom, developers have been bringing forward pumped storage projects, as the market requirements are clear.

In Italy, energy storage systems have access to two mechanisms: the *Meccanismo di Approvvigionamento di Capacita di Stoccaggio Elettrico* (MACSE) and the traditional capacity market. MACSE, a dedicated mechanism for energy storage, is designed to promote energy shifting as a flexibility product to be traded in the market so as to mitigate overgeneration, particularly in Southern Italy and the Islands, where renewable deployment is expected to be highest. By contrast, the capacity market focuses on assuring resource adequacy, rewarding the availability of stored electricity during peak demand periods.

In the United States, the California Independent System Operator (CAISO), which manages California's electricity market and grid operations, has introduced several initiatives to enhance energy storage participation. One of these is the package of Day-Ahead Market Enhancements (DAME), which improve the efficiency and flexibility of CAISO's day-ahead market by optimising scheduling and dispatch for energy storage, thereby allowing for better integration with VRE. Additionally, the Extended Day-Ahead Market (EDAM) expands the scope of CAISO's day-ahead market beyond California, enabling cross-border energy trading between regions. Broader market participation allows energy storage assets to access multiple revenue streams while improving grid reliability across a larger geographical area. Meanwhile, in the United Kingdom, the ability to access the country's Capacity Market and open ancillary service markets has resulted in a surge in battery investments, although a requirement to begin operating within four years of being awarded a capacity agreement militates against technologies like pumped storage, which have longer construction times.

A common issue for storage is the development of market mechanisms and business models. It is necessary to establish appropriate short- and long-duration storage markets to address the problem of infrequent utilisation throughout the year, while ensuring that projects remain economically sustainable. For storage assets that provide deep resilience to electricity grids – as well as significant upfront costs and long payback periods – pricing mechanisms should provide robust long-term visibility of revenues to encourage investors to deploy (IEA, 2023).

3.2.2 Policies and financial incentives

The three main services that energy storage can perform for the grid are 1) energy arbitrage; 2) ancillary services; and 3) resource adequacy. A supportive policy and regulatory framework is essential for these services. Business models for storage must offer access to multiple value streams and recognise their value to the grid, to renewable integration and to the electricity system as a whole. Revenues from certain services are often insufficient to support storage development, making the concept of revenue stacking essential for recovering storage costs.

Clear market rules, appropriate remuneration mechanisms and updated grid codes are also essential for enabling energy storage systems to participate in all relevant services. Long-term regulated incentives contribute to the bankability of storage projects. Clear permitting processes, with well-defined timelines and rules, can accelerate the deployment of storage projects and reduce development uncertainty.

In the case of energy storage systems, the potential for arbitrage income derives from buying power cheaply when there is a surplus of VRE and reselling it at a higher price when there is a deficit. Market arrangements should make it possible to price for scarcity at the peak and to acquire surplus power cheaply. Pay-as-clear mechanisms (where the price for all suppliers is based on the highest bid) can ensure that prices reflect real scarcity. Regulators should avoid capping or narrowing those price spreads. Should regulators decide to impose a price ceiling to protect final consumers, they should introduce additional long-term incentive schemes (such as the Capacity Market in the United Kingdom), to ensure system reliability and investment signals. Regulators should have a tolerance for high volatility in prices. Without day-ahead or intraday markets (see Section 3.2.1) storage operators will not be able to extract the value of being available at times of peak need if arbitrary limits are placed on the gap between peak and trough prices (IHA, 2024).

A number of countries are introducing mechanisms to provide long-term revenue visibility for long-duration energy storage. In the United Kingdom a proposed cap-and-floor mechanism would provide a guaranteed minimum revenue (the floor) in return for excess revenues being returned to consumers. The scheme partially replicates measures in New South Wales, Australia (AEMO Services, 2025; Ofgem, 2025). In Italy the Transmission System Operator (TERNA) is responsible for managing the allocation of fixed-price contracts through an auction mechanism open initially to batteries but eventually to a range of technologies under the MACSE scheme (Timera Energy, 2025).

Other ways to provide revenue stability can include access to a capacity payment, fixed over a long period, and/or long-term contracts for energy arbitrage and ancillary services. Policy makers should be careful to balance the disaggregation of revenue streams with the need to stabilise overall revenue to bring down risks. Cap-and-floor approaches are one way to do this, but other policy measures, such as contracts for difference (CfDs), may be more appropriate for different market designs.

In addition, a policy framework is needed to accelerate the adoption of solar PV and storage. Governments are supporting the deployment of battery storage with targets, subsidies and reforms that remove regulatory barriers and improve access to markets. Countries that have established clear targets and strong policies – and have created an enabling environment – are leading the way with significant annual increases in battery storage capacity additions, speeding progress toward a more resilient and flexible energy system.

In China, the first national target was set in 2020 to install 30 GW of additional energy storage by 2025. Driven by national policy, regional deployment would achieve almost 80 GW by 2025. Provinces have followed suit and extended the policy to solar PV, with recommended pairing rates between 5% and 30%. In the United States, the Department of Energy introduced Storage Innovations 2030 (SI 2030) goal to achieve 90% cost reductions by 2030 for technologies that provide 10 hours or longer of energy storage. Nine states have adopted storage targets, amounting to more than 50 GW of cumulative additions over the next 20 years. In the European Union, member states are collectively targeting deployment of around 45 GW of storage by 2030 through their national energy and climate plans. Several Member States provide support for battery storage. Italy, Germany and Sweden have implemented reforms to eliminate the double charging of taxes and wheeling charges for storage.

3.2.3 Stimulating investment through insurance mechanisms

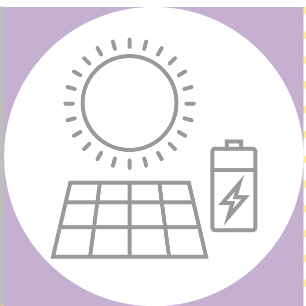
Solar PV and storage are effective at addressing climate change by promoting global electrification and renewable energy. However, to achieve a tripling of renewable power capacity by 2030, the annual average investment in renewable power generation in the 2023-2030 period will need to be USD 1 300 billion, compared to USD 486 billion in 2022 (IRENA, 2024a).

The development of solar PV and storage still faces hurdles, in part because, under current pricing mechanisms, storage is perceived as an additional cost item. Current credit rating methodologies penalise low-income countries, inflating their cost of capital and deterring private and public investment (Sachs *et al.*, 2025). Necessary financial tools such as fiscal incentives or diversified financial products, coupled with derisking mechanisms such as blended finance, are required to enable solar PV and storage to develop more successful business models. Financial products such as hedges and swaps can help stabilise revenues and thus reduce the cost of capital, but these come at a cost; revenue underpinning using a government policy mechanism may be more effective, as discussed in the next section.

In cases where technical, economic, and market risks, as well as policy-related risks, may dampen investors' willingness to support solar PV and storage integration, insurance services can be an effective de-risking instrument (see Table 1). Technical risk protection can be provided, covering damage to equipment and degradation of performance. Insurance services can also mitigate financial penalties or lost revenue resulting from a project's failure to meet a system's dispatching requirements, including delayed response or insufficient output. Insurance services also provide financing support, reduce the initial cost for solar PV and storage, and help operators deal with the uncertainties arising from market mechanisms and policy, ensuring projects' sustainable development.

Table 1 **Proposed insurance products and services for solar PV and storage application**

RISK AND CHALLENGES	PRODUCTS AND SERVICES AVAILABLE FROM INSURANCE INSTITUTIONS
Technology Maturity and Stability	• Technical risk coverage for solar PV and storage application, including equipment damage and performance degradation, ensuring timely economic compensation when facing technical issues. • Financial compensation in case of losses due to insufficient system response, alleviating the economic pressure on project operators.
Market and Policy	• Risk coverage and financial support. • Market risk mitigation arising from policy uncertainty by offering stable economic protection and expected returns to project developers.



3.3. The essential role of standards and certification

Standards and certification are critical to the scaling up of solar PV and storage to meet demand. They must cover research and development (R&D), safety evaluation, supply chain compliance and life-cycle management.

Battery storage deployments are highly complex, with more than 1.5 million components. When connected to the grid, system failures can lead to serious consequences such as regional blackouts and economic and environmental consequences. Stringent quality control procedures can prevent such incidents. Robust safety testing helps identify potential hazards and design flaws before systems are deployed.

Extensive standards and certifications already exist for the solar PV industry. The main challenge is convincing market participants to accept the importance and value of compliance with international standards, and of inspection and certification to meet those standards (IRENA, 2024d).

A standards system has been established for storage by the International Electrotechnical Commission (IEC). It covers a range of topics from batteries to systems, as shown in Table 2. IEC/TC 120 provides standards at the energy storage system level, covering terminology, parameters and testing, planning and installation, environmental issues, and safety. IEC/SC21A/WG5 is largely devoted to standards for lithium-ion batteries, focusing on battery safety and performance requirements.

However, some issues require further improvement. Currently, the standards focus on pre-grid connection and lack coverage of energy storage systems in operation. There is a need to supplement standards for maintenance, repair, performance evaluation, and regular testing of operating storage stations to further cover the full life-cycle of energy storage systems. Also, the current IEC 62933 series provides relatively general provisions for energy storage systems, with limited operability. The requirements for different application scenarios should be clarified and refined so as to better guide and regulate the safety design of energy storage systems.

Table 2 International standards for battery storage

STANDARD ID	TITLE
IEC 62933-1:2024	Electrical energy storage (EES) systems - Part 1: Vocabulary
IEC 62933-2-1:2017	EES systems - Part 2-1: Unit parameters and testing methods - General specification
IEC 62933-2-1:2017/COR1:2019	Corrigendum 1 - EES systems - Part 2-1: Unit parameters and testing methods - General specification
IEC TS 62933-2-2:2022	EES systems - Part 2-2: Unit parameters and testing methods - Application and performance testing
IEC TR 62933-2-200:2021	EES systems - Part 2-200: Unit parameters and testing methods - Case study of electrical energy storage (EES) systems located in electrical vehicle charging station with PV
IEC TR 62933-2-201:2024	EES systems – Part 2-201: Unit parameters and testing methods – Review of testing for battery energy storage systems (BESS) for the purpose of implementing repurpose and reuse batteries
IEC TS 62933-3-1:2018	EES systems - Part 3-1: Planning and performance assessment of electrical energy storage systems - General specification
IEC TS 62933-3-2:2023	EES systems - Part 3-2: Planning and performance assessment of electrical energy storage systems - Additional requirements for power intensive and renewable energy sources integration related applications
IEC TS 62933-3-3:2022	EES systems - Part 3-3: Planning and performance assessment of electrical energy storage systems - Additional requirements for energy intensive and backup power applications
IEC TS 62933-4-1:2017	EES systems - Part 4-1: Guidance on environmental issues - General specification
IEC 62933-4-4:2023	EES systems - Part 4-4: Environmental requirements for battery-based energy storage systems (BESS) with reused batteries
IEC TR 62933-4-200:2024	EES systems - Part 4-200: Guidance on environmental issues - Greenhouse gas (GHG) emissions assessment by EES systems
IEC 62933-5-1:2024	EES systems - Part 5-1: Safety considerations for grid-integrated EES systems - General specification
IEC 62933-5-2:2020	EES systems - Part 5-2: Safety requirements for grid-integrated EES systems - Electrochemical-based systems
IEC 62933-5-3:2023	EES systems - Part 5-3: Safety requirements for grid-integrated EES systems – Performing unplanned modification of electrochemical based system
IEC 62619:2022	Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for secondary lithium cells and batteries, for use in industrial applications
IEC 63056:2020	Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for secondary lithium cells and batteries for use in electrical energy storage systems
IEC 62620:2014	Secondary cells and batteries containing alkaline or other non-acid electrolytes - Secondary lithium cells and batteries for use in industrial applications

Source: (IEC, 2025).

3.3.1 The imperative of ensuring safety in electrochemical energy storage

Energy storage systems are often placed in harsh environments or are exposed to extreme working conditions and overuse. Therefore, ensuring system-level storage safety needs to take into account both chemistry selection within the cells – lithium-iron-phosphate is more stable and thus safer to be deployed in energy storages than the widely used nickel manganese cobalt oxide (NMC) and system components being integrated, such as power conversion systems (PCS) and battery management systems (BMS).

Grid safety also necessitates comprehensive safety protection from the battery cell level to the system level. Since 2011, more than 100 safety accidents have been reported globally across various storage technologies. In 2023 alone, 20 incidents of energy storage station accidents occurred globally; 19 were nickel manganese cobalt (NMC) oxide projects, while one was a thermal energy storage project (CNESA, 2024).

Currently, systematic evaluations of energy storage safety are relatively limited, and further evaluations must be made to enhance safety. Establishing a more comprehensive and systematic safety evaluation guidance system and developing multi-factor safety rating methods for energy storage have become important for promoting the development of high-quality energy storage.

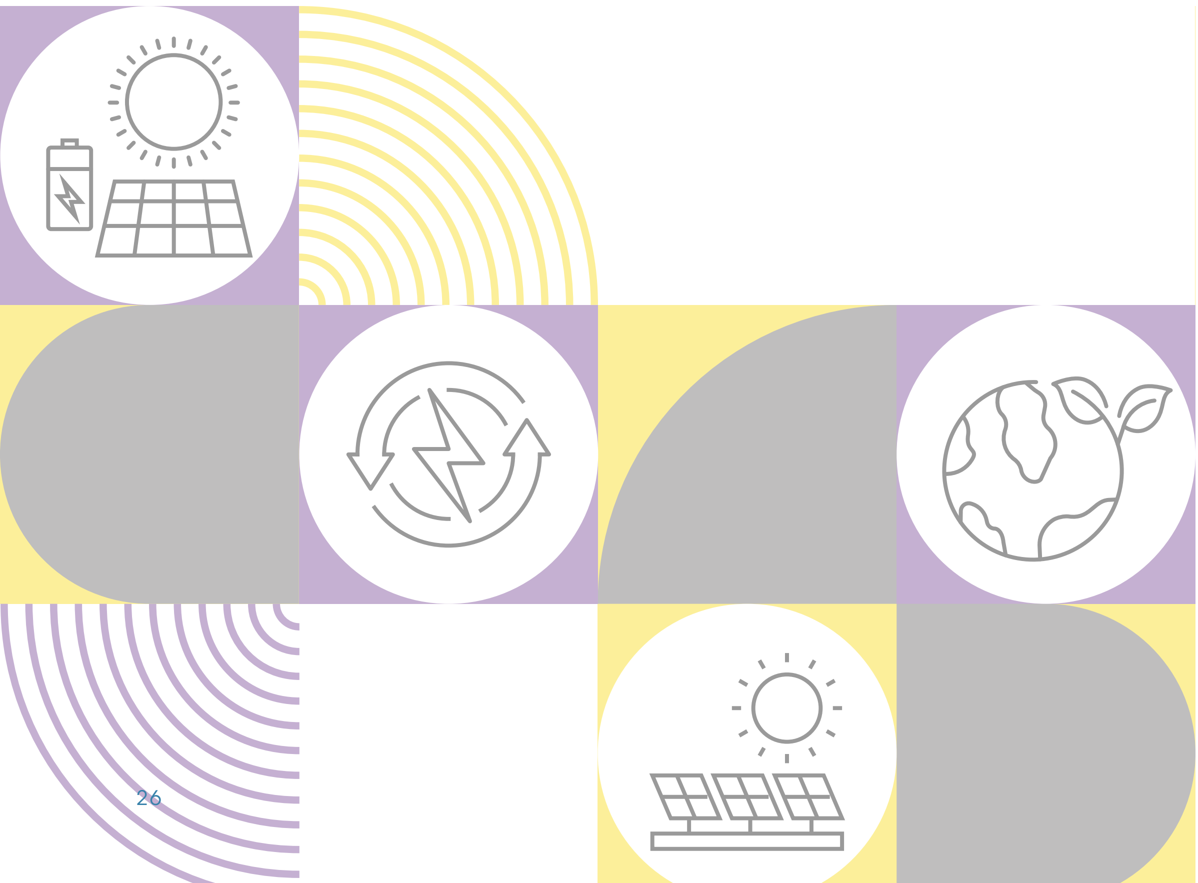
3.3.2 Grid integration safety

Power conversion systems (PCS) must ensure a safe and reliable interaction with the grid. Currently, globally harmonised standards for medium-voltage cascaded converters and grid-forming converters for storage applications are lacking, and some grid-connection standards have not fully encompassed the characteristics of energy storage systems, instead applying standards developed for VRE. As new power systems evolve and energy storage systems develop, grid-connection standards for energy storage must be continuously updated to meet future grid challenges. For example, it will be important to enhance the requirements for dynamic compatibility and disturbance resilience of power conversion systems used for energy storage under grid conditions such as islanding mode and fault ride-through.

To deepen the understanding of grid-integration mechanisms, China has established a testing platform based on the centre in Zhangbei National Large Wind Power Grid-connected System R&D (Testing) Center. The United States has also set up an energy storage testing platform at the National Renewable Energy Laboratory (NREL). However, both platforms are limited to small-scale, megawatt-level storage validations and cannot meet the testing needs of high-voltage, large-capacity, multi-unit energy storage validation. In addition, China is currently constructing the Xiamen Validation Institute, which will provide 35 kV, 100 MVA (megavolt ampere) testing interfaces, effectively validating station-level renewable energy grid-connection characteristics, including energy storage. The series of methods would ensure the safe and stable operation of grids with a high proportion of renewable energy integration. It would also allow for exploration of the role of energy storage in new power systems.

3.3.3 Grid data security

Modern power systems exist at the physical as well as the digital level, where information systems are an essential component. Energy storage systems are composed of large numbers of battery cells generating large amounts of data that can be included in the scope of power system safety management when the cells are integrated with the grid. Thus, data security can be enhanced by the information management model used by the existing power system. Given the sensitivity of power-system data, systems that incorporate energy storage must implement robust security measures to safeguard data security and ensure stable operation. Grid management should establish clear mechanisms for data monitoring and enforce standardised practices for data storage, transmission, and validation. In this regard, international standards can be crucial for selecting suitable technologies to ensure data security. Additionally, energy storage data should also be incorporated into broader safety management frameworks, enabling seamless data exchange between different systems and fostering interoperability, data transmission and further collaboration.



4. RECOMMENDATIONS

This section offers recommendations on how to expand the use of solar PV and storage to enhance grid flexibility and accelerate the decarbonisation of energy systems. Policies to implement these recommendations will significantly contribute to achieving the international target of tripling renewable power capacity by 2030.

Promote storage as a key enabler for achieving global renewable energy targets and climate goals

- **Adopt energy storage targets to accelerate investments in storage capacity**
  - » A collective commitment to adding storage capacity will smooth the integration of increasing shares of renewable power capacity. Assessments of existing national storage capacities, as well as other grid flexibility options, should be conducted to gauge their adequacy to accommodate already committed deployments of renewable capacity.[2] Where possible, off-grid storage potential should also be identified.
  - » Energy development plans that include storage targets will prepare the system to accommodate rising shares of VRE. The targets should cover both short- and long-duration energy storage for voltage and frequency control and for intraday, weekly, monthly and seasonal power management.

- **Develop action plans to redress skilled labour shortages**
  - » Assessments should be conducted to identify gaps in the renewable energy workforce and related skillsets. Specialised training for relevant professionals is needed in both solar installations and energy storage deployments. A just and inclusive transition must actively address the challenges of structural change and therefore prioritise support for fossil fuel-dependent regions and workers to ensure that the energy transformation unfolds in a socially acceptable way. Fossil-fuel workers are excellent targets for training in the skills and specialisations needed to fulfil renewable and energy storage roles.

Enhance energy storage deployment to support grid flexibility and stability

- **Enhance the technical capacity to undertake grid-forming solutions**
  - » The increased penetration of VRE in grids requires enhanced grid flexibility and should be prioritised by policy makers. VRE combined with energy storage and other flexibility solutions will significantly enhance grid stability and reliability.

[2] *An example includes IRENA's FlexTool, which performs power system flexibility assessments based on national capacity investment plans and forecasts.*

- **Establish national and sub-national storage commitments based on flexibility needs and forecasts of supply and demand**
  - » Grid flexibility is key for energy systems that contain high shares of renewable energy. Flexibility accommodates the output variability of renewable energy, providing fast-response capabilities, deferring or reducing the need for investments in grid expansion, and supporting the operation of electricity markets.
  - » The global power system, including regional growth in power load, should be analysed to determine the strategic optimisation and integration of grid developments. The analytical process should include the setting of country-level interim (*e.g.* 2030) energy storage targets that build on supply and demand forecasts and predicted flexibility needs.
- **Improve and flesh out the regulatory framework for integrating energy storage into the grid and ensure that mechanisms to secure investments are in place**
  - » A comprehensive regulatory framework is essential for the smooth and rapid integration of energy storage into the grid. That framework must encompass clear technical standards and investment incentives. Regulatory predictability is critical for attracting capital-intensive investments in energy storage, as it allows operators to make informed and bankable decisions. Grid tariffs should be set with an intention to providing a level playing field for storage as an attractive flexibility option in the market.

Develop solar PV and storage through favourable financing and insurance policies

- **Provide long-term commercial viability to the energy storage industry**
  - » Energy storage providers should be established as independent, participants in electricity markets. Storage should be recognised as an independent, bi-directional charging and discharging entity within the grid system and should not be subject to double network fees for charging and discharging, only one fee should apply. Policies and financial incentives are needed to offer the energy storage industry a sustainable business model and market predictability. In short, energy storage should no longer be treated as a cost but rather as an asset providing added value for VRE.
- **Introduce diversified financial mechanisms**
  - » In addition to ensuring a level playing field, fiscal incentives are a prerequisite for mass adoption of renewable energy technologies. These incentives can include preferential tariffs, feed-in tariffs, capital subsidies for relevant equipment, reward schemes tied to energy savings and emissions reductions, and other policy and regulatory tools. A collective action platform – such as an investment alliance comprising banks, regulatory bodies, suppliers, financial institutions and energy service companies – could help channel financial resources from private equity investors to the renewable energy sector.

  - For emerging economies, tailor-made grants from public sources in developed economies should include support for 1) grid development; 2) storage capacity; 3) domestic development and manufacturing of renewable energy technologies and infrastructure components; 4) labour skilling; and 5) education.

- **Ensure that favourable insurance policies are available**
  - Solar PV and storage are currently facing several barriers to deployment, such as high initial investment requirements and policy uncertainties. Insurance services can play a crucial role in overcoming these obstacles for solar PV and storage integration. Specifically, insurance services can offer protection against losses due to technical risks such as equipment failure. They could also provide more options in terms of financial support – such as premium financing – to build investor confidence and help developers navigate through competition and policy uncertainties.

Support the development of standards and certifications

- **Encourage participation, compliance and implementation**
  - International collaboration – in the form of technical committees where international standards are developed – must be encouraged. Platforms are needed to develop industry standards. An example is the International Quality Infrastructure Forum, which ensures that components for solar PV and storage are technically sound and safe. Different stakeholders across governments, industry associations and the private sector should be encouraged to participate.

- **Design systematic technologies to support the development of standards and innovation**
  - It is necessary to develop equipment and technologies for testing and validation, leveraging R&D to provide reference points for the development of solar PV and energy storage standards. Governments can maintain and expand support for R&D at public universities and research institutions to encourage advances in innovation and technology that reduce risks and costs and improve grid services. Private laboratories that meet stringent certification requirements can also participate in testing and evaluation programs.

- **Establish global consensus on standards for safety evaluation**
  - The successful development of the solar PV and energy storage industries relies on establishing consensus on shared safety standards. Safety requirements for energy storage products vary owing to differences in the materials used and manufacturing processes employed. Although many standards have already been introduced in

various markets in different parts of the world, the existing body of mandatory safety standards is insufficient and not globally adjusted, especially for battery storage. At the system level, many norms still follow voluntary principles and are not formally established. Global, industry-wide safety procedures will depend on harmonising and formally adopting existing standards.

- **Promote supply chain compliance and diversification**
  - » Resilient and efficient supply chain networks that facilitate rapid, timely and cost-effective delivery must be developed and secured. Improvements to the security and resilience of solar PV and storage supply chains require a better understanding of risks while also maintaining fair trade practices. The environmental, social and financial sustainability of these industries must be improved by ensuring compliance with international quality and certification standards. Labour rights need to be respected, and robust project documents and/or auctions must also be developed and followed. This includes responsible mining and the processing and recycling of critical materials needed for supply chain diversification.
- **Conduct life-cycle assessments of battery storage stability and reuse, recycling and end-of-life disposa**l
  - » Safe operation of battery storage assets must be ensured. Over time, the stability of battery materials tends to decrease, raising the level of safety hazards. To address this challenge, safety standards and testing guidance are needed specifically for energy storage products with long charging and discharging cycles.
  - » Recycling of battery storage materials needs to be considered throughout project life-cycles. Batteries should be designed with longevity and recyclability in mind. Recycling and waste management technologies and practices during production must be improved. A practical model for recycling systems needs to be developed and commercialised.

REFERENCES

AEMO Services (2025), "AEMO Services' NSW long duration storage tender awards more than 1GW and 13GWh", https://aemoservices.com.au/news/media-release/250227-asl-nsw-long-duration-storage-tender-awards-more-than-1gw-and-13gwh.

BEE (2025), "Renewable Consumption Obligations (RCO)", Bureau of Energy Efficiency of India, https://beeindia.gov.in/renewable-consumption-obligations-rco.php (accessed 11 August 2025).

BNEF (2024), *1H 2024 energy storage market outlook*, BloombergNEF, New York, https://about. bnef.com/blog/global-energy-storage-market-records-biggest-jump-yet.

BNEF (2025), "Headwinds in largest energy storage markets won't deter growth", https://about.bnef.com/insights/clean-energy/global-energy-storage-growth-upheld-by-new-markets (accessed 11 August 2025).

CNESA (2024), "The price of energy storage is 'involution', who will pay for safety?", www.cnesa.org/information/detail/?column_id=58&id=6601 (accessed 28 August 2025).

COP29 Presidency (2024), "Global Energy Storage and Grids Pledge", COP29, https://cop29.az/en/pages/global-energy-storage-and-grids-pledge-background-information (accessed 26 November 2024).

CPIA (2024), "China's PV Industry Roadmap (2023-2024)", China Photovoltaic Industry Association, www.chinapv.org.cn/Handler/FileInfo.ashx?file=1380_1.

Government of India (2025), "PM Surya Ghar: India's Solar Revolution", www.pib.gov.in/PressReleaseIframePage.aspx?PRID=2111106 (accessed 11 August 2025).

IEA (2024), *World energy outlook 2024*, International Energy Agency, Paris, https://iea.blob.core.windows.net/assets/5e9122fc-9d5b-4f18-8438-dac8b39b702a/WorldEnergyOutlook2024.pdf.

IEA (2025), *Global energy review*, International Energy Agency, Paris, https://iea.blob.core.windows.net/assets/5b169aa1-bc88-4c96-b828-aaa50406ba80/GlobalEnergyReview2025.pdf.

IEC (2025), "Electrical energy storage management system", https://syc-se.iec.ch/iec-63097-smart-energy-roadmap/electrical-energy-storage-management-system (accessed 28 August 2025).

IHA (2021), "Pumped Storage Hydropower: Capabilities and Costs", International Hydropower Association, www.hydropower.org/publications/pumped-storage-hydropower-capabilities-and-costs.

IHA (2024), *World Hydropower Outlook 2024*, International Hydropower Association, London, www.hydropower.org/publications/2024-world-hydropower-outlook.

IRENA (2019), *Innovation landscape brief: Future role of distribution system operators*, (p. 20), International Renewable Energy Agency, Abu Dhabi, www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Feb/IRENA_Landscape_Future_DSOs_2019.pdf.

IRENA (2023), *The changing role of hydropower: Challenges and opportunities*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2023/Feb/The-changing-role-of-hydropower-Challenges-and-opportunities.

IRENA, COP28, *et al.* (2024), *Delivering on the UAE Consensus: Tracking progress toward tripling renewable energy capacity and doubling energy efficiency by 2030*, International Renewable Energy Agency, COP28 Presidency, COP29 Presidency, Global Renewables Alliance, Ministry of Energy of the Republic of Azerbaijan, Government of Brazil, Abu Dhabi, www.irena.org/Publications/2024/Oct/UAE-Consensus-2030-tripling-renewables-doubling-efficiency.

IRENA (2024a), *Renewable power generation costs in 2023*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2024/Sep/Renewable-Power-Generation-Costs-in-2023.

IRENA (2024b), *Renewable energy statistics 2024*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2024/Jul/Renewable-energy-statistics-2024.

IRENA (2024c), *Tripling renewable power by 2030: The role of the G7 in turning targets into action*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2024/Apr/Tripling-renewable-power-by-2030-The-role-of-the-G7-in-turning-targets-into-action.

IRENA (2024d), *Solar PV supply chains: Technical and ESG standards for market integration*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2024/Sep/Solar-PV-supply-chains-Technical-and-ESG-standards-for-market-integration.

IRENA (2024e), *Energy taxonomy: Classifications for the energy transition*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2024/Mar/Energy-taxonomy-Classifications-for-the-energy-transition.

IRENA (2024f), *World energy transitions outlook 2024: 1.5°C pathway*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2024/Nov/World-Energy-Transitions-Outlook-2024.

IRENA (2025a), *Renewable capacity statistics 2025*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2025/Mar/Renewable-capacity-statistics-2025.

IRENA (2025b), *Renewable power generation costs in 2024*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/-/media/Files/IRENA/Agency/Publication/2025/Jul/IRENA_TEC_RPGC_in_2024_2025.pdf.

IRENA and ILO (2024), *Renewable energy and jobs: Annual review 2024*, International Renewable Energy Agency and International Labour Organization, Abu Dhabi, www.irena.org/Publications/2024/Oct/Renewable-energy-and-jobs-Annual-review-2024.

IRENA and UNEZA (2024), "Global Utilities Back COP29 Pledge to Boost Grids and Storage in Strong Implementation Signal", www.irena.org/News/pressreleases/2024/Nov/Global-Utilities-Back-COP29-Pledge-to-Boost-Grids-and-Storage-in-Strong-Implementation-Signal (accessed 29 November 2024).

IRENA and WMO (2023), *2022 Year in review: Climate-driven Global Renewable Energy Potential Resources and Energy Demand*, World Meteorological Organization and International Renewable Energy Agency, Geneva and Abu Dhabi, www.irena.org/Publications/2023/Dec/2022-Year-in-Review-Climate-driven-Global-Renewable-Energy-Potential-Resources-and-Energy-Demand.

LDES Council (2024), "2024 Long Duration Energy Storage Council Annual Report", www.ldescouncil.com/assets/pdf/2024_LDES_Annual_Report.pdf.

NDRC (2024), "Action Plan for Accelerating the Construction of a New Power System (2024-2027)", www.ndrc.gov.cn/xwdt/tzgg/202408/t20240806_1392260.html.

NSEFI (2025), "Indian Solar Manufacturing Landscape, Outlook and Opportunities", https://images.assettype.com/taiyangnews/2025-04-22/mpt8jxaf/STCI_1_1_2_NSEFI_Subrahmanyam_Pulipaka.pdf (accessed 11 August 2025).

OFGEM (2025), "Long Duration Electricity Storage", UK Government Office of Gas and Electricity Markets, www.ofgem.gov.uk/energy-policy-and-regulation/policy-and-regulatory-programmes/long-duration-electricity-storage (accessed 1 May 2025).

O'Shaughnessy, E., Cruce, J., et al. (2021), "Solar PV Curtailment in Changing Grid and Technological Contexts", Presented at *2019 CIGRE Grid of the Future Symposium*, Atlanta, Georgia, https://docs.nrel.gov/docs/fy21osti/74176.pdf (accessed 1 September 2025).

O'Shaughnessy, E., and Shah, M. (2021), "The Demand-Side Opportunity: The Roles of Distributed Solar and Building Energy Systems in a Decarbonized Grid", https://docs.nrel.gov/docs/fy21osti/80527.pdf (accessed 1 September 2025).

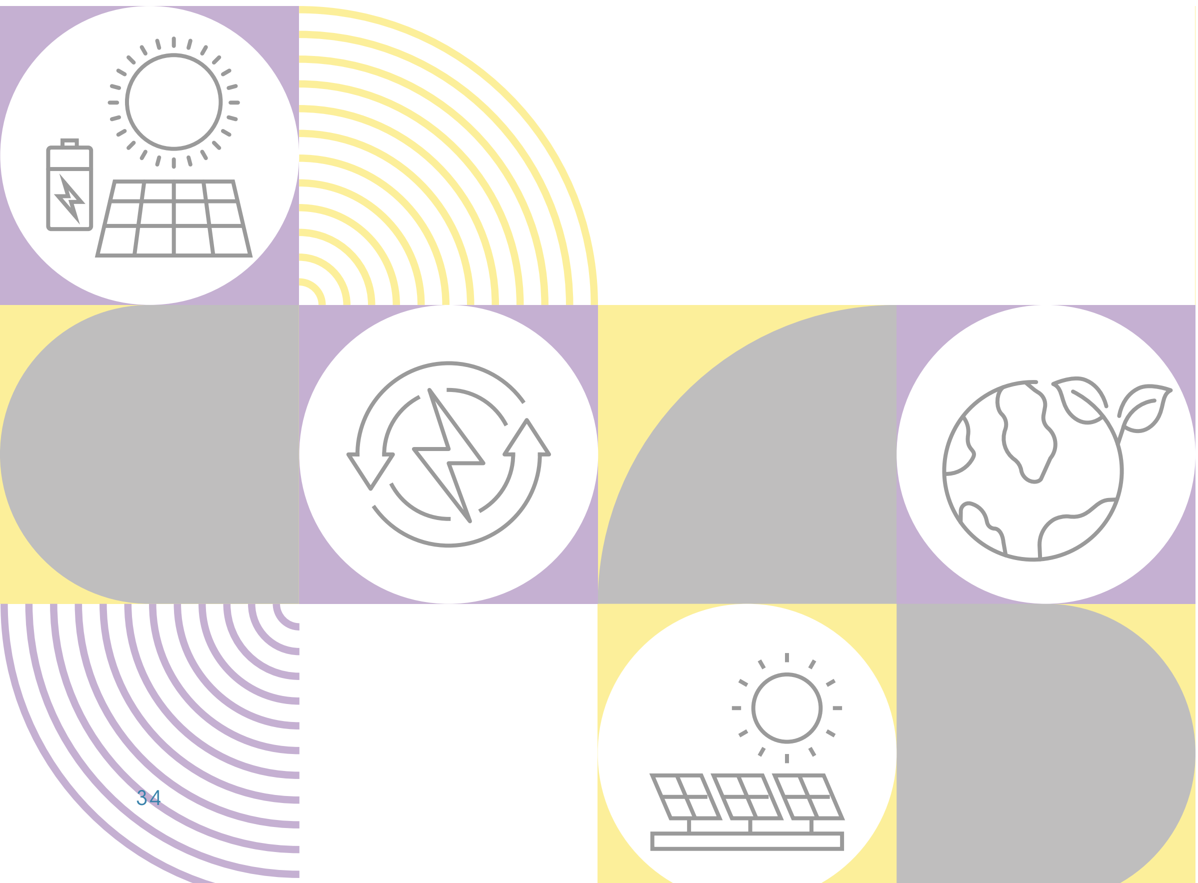
Reuters (2025), "KKR-backed ContourGlobal acquires energy storage projects in Italy", www.reuters.com/business/energy/kkr-backed-contourglobal-acquires-energy-storage-projects-italy-2025-07-03 (accessed 21 August 2025).

Sachs *et al.* (2025), "Lowering the Cost of Capital for Climate and SDG Finance in Emerging Markets and Developing Economies (EMDEs)", Columbia Center on Sustainable Investment (CCSI), https://ccsi.columbia.edu/sites/ccsi.columbia.edu/files/content/docs/publications/CCSI-Cost-of-Capital-in-EMDEs.pdf (accessed 6 August 2025).

SolarPower Europe (2024a), "Mission Solar 2040: Europe's flexibility revolution", www.solarpowereurope.org/insights/thematic-reports/mission-solar-2040-1.

SolarPower Europe (2024b), "EU Market Outlook for Solar Power 2024-2028", www.solarpowereurope.org/insights/outlooks/eu-market-outlook-for-solar-power-2024-2028.

Timera Energy (2025), "Italy's 1st MACSE auction: green light for BESS investors", https://timera-energy.com/blog/italys-1st-macse-auction-green-light-for-bess-investors (accessed 1 May 2025).



ANNEX: SOLAR PV AND STORAGE CASE STUDIES

PROJECT	Ordos Green Power Supply: Research and Application Demonstration Project of the "Zero-Carbon Super Generator Set"	Grid Booster, Kupferzell	Blackhillock Project
SCALE	660 000 kW of wind power, 340 000 kW of solar power, and 160 000 kW/4 hours of electrochemical energy storage	Pilot	200 MW / 800 MWh
LOCATION	Ordos, China	Kupferzell, Germany	Blackhillock, Scotland
DATE	2023 – 2024	The project was initiated in 2019 and is expected to be completed in 2025	2023 – 2024
CHALLENGES	In recent years, the concept of "eco-industrial parks (EIPs)" has increasingly been recognised as an effective tool in overcoming challenges related to inclusive and sustainable industrial development within the scope of the UN Sustainable Development Goals (SDGs). Countries such as Denmark, France, Japan and the Republic of Korea have leveraged key elements of the EIP concept to promote more inclusive and sustainable action to improve industrial competitiveness in line with climate change goals.	The current transmission grid is heavily utilised. Energy transport from North to South, in particular, is increasingly challenging for transmission system operators. This is because the power lines are currently being utilised below their capacity limit to protect against overloads. In addition, so-called 'preventive redispatch' measures are used, in which power plants are switched off upstream of the starting point of the overloaded line and ramped up again downstream of the end point. These measures are necessary to secure the power supply. However, they are expensive, and counter-productive to the goals of the energy transition.	Lack of stability due to retirement of conventional synchronous generation and increase of inverter-based resource (IBR) power generation

SOLUTIONS	Zero-carbon parks represent a new commercial model for solar and storage applications. Typically situated in high-energy-consumption industrial parks, they integrate solar and storage solutions with other smart energy management systems (including flexible conversion of electricity, heating and cooling). This project aims to provide green electricity to high-energy-consuming enterprises and establish a new business model for direct renewable energy supply to industrial parks. The energy storage system utilises a high-voltage direct current (HVDC) energy storage technology route, which includes a storage valve and a flexible direct current (DC) converter valve. Compared to traditional low-voltage storage solutions, the HVDC direct storage system features a large capacity, high efficiency and strong support. It operates independently without the need for diesel generators or grid support, achieving self-frequency/voltage regulation, self-inertia regulation, grid connection and disconnection, and island operation functions, thus establishing the world's first "zero-carbon industrial park" scenario demonstration. By leveraging local peak-valley price differentials, regional subsidies and future carbon emission market designs, high-carbon industries can reduce operation costs and achieve emissions reduction. In addition to China, the zero-carbon park model is expected to be replicated and expand into other markets in the future.	With the help of a Grid Booster, the existing transmission grid can be utilised to a greater extent than before. This is because a Grid Booster is able to compensate for potential transmission grid overloads in a matter of seconds by (partially) automatically feeding in stored energy downstream of the bottleneck and reducing the feed-in after the bottleneck. The Grid Booster balances out the overload for up to one hour until curative measures such as the connection of power plants downstream of the bottleneck, switching measures or feed-in management are implemented. The Grid Booster Kupferzell has a capacity of 250 MW, making it one of the largest grid battery storage systems in the world.	The Blackhillock project is an initiative aimed at advancing the UK's transition to a net-zero economy by 2050. Blackhillock is part of the National Grid Electricity System Operator's (NGESO) Stability Pathfinder project, which aims to purchase grid-stability services from diverse asset classes. This project leverages inverter and battery technology to enhance grid stability and integrate more renewable energy into the national grid. Initially focusing on synchronous condensers, the project has now expanded to include grid-forming inverter assets, diversifying the range of stabilisation solutions available. The Blackhillock battery project, with a capacity of 200 MW / 400 MWh, will provide a full suite of energy, ancillary, and stability services. The implementation of this project is expected to reduce consumer bills by over USD 220 million over 15 years and contribute to energy independence.
IMPACTS AND BENEFITS	The project has a total investment of approximately USD 820 million. It will be built with an annual power generation capacity of about 2730 GWh, allowing for a renewable electricity supply ratio of ≥80% for enterprises. The project implemented multi-purpose assets based on Battery Energy Storage System (BESS) energy arbitrage, ancillary service and stability services.	The project is expected to enhance grid stability and resilience, lower operational costs and support the broader integration of renewable energy sources into the grid, ultimately making the energy transition more sustainable and economically viable.	The project implemented multi-purpose assets based on BESS energy arbitrage, ancillary service and stability services in a marked based tender. In terms of socio-economic and environmental benefits, the project not only supports the UK's net-zero objectives but also enhances energy efficiency and stability, contributing to a more sustainable and resilient energy infrastructure.

IRENA

International Renewable Energy Agency

www.irena.org